The potential and limitations of satellite observations for CO_2 retrievals over boreal forests

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Abstract – This paper considers various problems related to the capabilities of satellite observations for retrieving CO_2 surface fluxes and atmospheric concentrations over boreal forests. A novel regression model suitable for calculating various components of CO_2 fluxes at the surface level and employing satellite data as input has been developed. Results of this model are validated against observations and compared to the results produced by the European LPJ dynamic global vegetation model and the Canadian ecosystem model EALCO. The comparison was conducted over two boreal sites (Canada (Manitoba) and Russia (Zotino)) and shows a satisfactory agreement between modeled and observed values. Initial CO_2 atmospheric column retrievals from SCIAMACHY onboard ENVISAT indicate that it is possible to detect reduced CO_2 atmospheric column amounts resulting from the uptake of CO_2 by growing vegetation. The potential of combined solar and thermal satellite observations and upcoming IASI/METOP for CO_2 monitoring is discussed.

Keywords: CO_2, boreal forest, satellite monitoring, SCIAMACHY, ENVISAT, MODIS, AIRS, IASI

1. INTRODUCTION

Carbon dioxide in the atmosphere has increased from about 280 ppmv to almost 380 ppmv since the beginning of industrial development, and has continued to grow at an average annual rate around 1.5 ppmv over the past several decades. This phenomenon has generated significant concern due to the strong effect of CO_2 on climate. Despite a long history of research and the knowledge gained from numerous studies, there are still significant gaps in our understanding of carbon budget globally, and over the boreal forest in particular. Net CO_2 fluxes (sources and/or sinks) are produced as small relative differences between large components, where the natural flux component dominates the anthropogenic one. To achieve any substantial progress in the characterization of carbon sinks and sources, the reliable space-time mapping of CO_2 surface fluxes and atmospheric content is required. Due to the nearly uniform mixing of CO_2, the determination of concentration of CO_2 in the boundary layer is of critical importance for closing the total CO_2 budget. Satellite observations can provide the required spatial and temporal sampling; however, achieving the accuracy required for the detection of CO_2 sources or sinks is a very challenging problem.

Two approaches are pursued in this paper. The first approach is aimed at the development of techniques suitable for assessing ecosystem carbon exchange at the surface level. Satellite remote sensing serves here as a tool to provide the required input information that is either unavailable from traditional ground observations (e.g. spatial maps of vegetation properties and radiation) or is used as a surrogate of other ground-measured parameters (e.g. near surface air temperature). Modeling of CO_2 exchange at the surface level can be conducted using dynamic ecosystem models or certain regression techniques where the major dependences between input and output characteristics are parameterized explicitly and tuned to the observations.

The second approach employs solar and thermal infrared spectroscopy techniques to retrieve CO_2 atmospheric contents. This information is a valuable input for inverse modeling aimed at determining the sources and sinks of CO_2 and is based on atmospheric transport, chemistry and surface ecosystem models. We provide the initial results of CO_2 retrievals from the SCIAMACHY/ENVISAT over Canadian and Siberian boreal forests and further discuss the potential development of improved algorithms for CO_2 retrievals.

For the validation and in-depth analysis of the algorithms, two boreal forest sites were identified. The first site was an Old Black Spruce (OBS) site located in the Northern Study Area (NSA) of the BOREAS (Boreal Ecosystem-Atmosphere Study) project region in Manitoba, Canada (55.9°N, 98.5°W). Comprehensive archive of surface meteorology and carbon flux data over the NSA OBS has been available since 1994. The second site was located in Zotino, Russia (60.8N, 89.3E), where data have been collected during several warm seasons starting 1998 as part of the European Terrestrial Carbon Observing System projects – Siberia, Siberia-I, Siberia-II.

This paper describes the results obtained during the initial stage of the project supported by the International Astronautics Federation through the BEAR initiative.

2. SURFACE CO_2 FLUXES OVER BOREAL SITES

2.1. CO_2 fluxes from ecosystem dynamics models and observations

Two models were used in this study to simulate carbon exchange in the boreal evergreen forest. The EALCO model

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** Work is supported by the International Astronautics Federation and the European Space Agency through the BEAR initiative and by the Canadian Space Agency (CSA) through the funding to the Canada Centre for Remote Sensing.

(Ecological Assimilation of Land and Climate Observations) was developed at the Canada Centre for Remote Sensing to study the ecosystem-climate interactions by assimilating Earth Observation data sets (both *in situ* and satellite). In the EALCO model, ecosystem processes of various land cover types are simulated by five main modules (radiation, energy, water, carbon, and nitrogen). The radiation component uses canopy multi-layer ray-tracing algorithms based on a gap probability approach (Wang, 2005). Multi-wavelength and the separation of direct vs. diffuse components for solar radiation are recognized in the model. The radiation module provides the output of net radiation for both canopy and the underlying ground surface. Canopy energy and water exchanges with the atmosphere are simulated by numerically solving the coupled energy and water balance equations. A flexible soil layering scheme, a dynamical snow layering scheme, and a water table and its interaction with soil water in the unsaturated soil layers were included in the model. Carbon exchange is obtained by simulating canopy gross photosynthesis. Growth respiration is calculated as a fraction of plant growth. Maintenance respiration is based on plant nitrogen content. Heterotrophic respiration is obtained from both surface litter fall and soil organic matter using first order kinetics (Wang et al., 2002). In EALCO, ecosystem water dynamics are closely related to the carbon and nitrogen dynamics through which the climatic and plant physiological controls on water cycles are simulated.

The second model was Lund-Potsdam-Jena (LPJ) dynamic global vegetation model described in (Sitch et al 2003). This model is freely available and well documented. Although the model was designed to simulate the average spatial and temporal parameters of the carbon cycle, it can be also applied for a particular site.

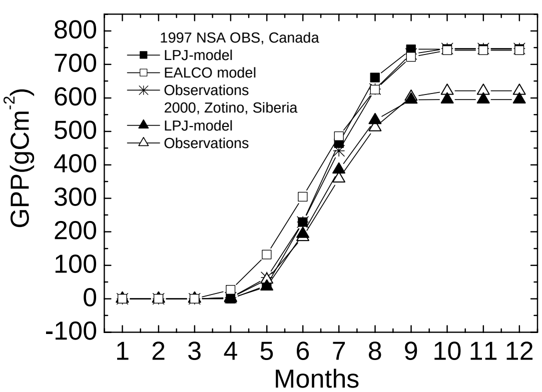

Figure 1. Comparison of Gross Primary Productivity (GPP) derived from ground observations and simulated by LPJ and EALCO models for BOEAS NSA and Zotino.

The above models were employed using locally estimated input parameters and forcing fields. Figure 1 shows accumulated Gross Primary Productivity (GPP) for 1997 for both sites. For the NSA OBS site, observed GPP was corrected for photorespiration. A good agreement was observed for annually accumulated GPP between observations and both models. The difference in the annual GPP accumulation between both models and observed results are less than 3 gC m^{-2} for the annual total around 746 gC m^{-2} for NSA OBS. For Siberian site Zotino this difference is -26 gC m^{-2} for the annual total 621 gC m^{-2} (-4%). The differences at the monthly scale can be larger, especially for the EALCO model. Presently this model was mostly tuned for broadleaf boreal forest, and needle leaf simulations are expected be improved in the future.

2.2. Development of the regression model

2.2.1. Input data and type of regression

The input data for developing the regression model were taken from both sites and combined to form a single data set. Data for the NSA OBS site were taken from the BOREAS archive (available at http://daacsti.ornl.gov/FLUXNET/fluxnet.html). The dataset described by Lloyd et al. (2002), and Lafont et al. (2002) were used for Zotino boreal site (http://www.bgc-jena.mpg.de/bgc-systems/projects/ web_TCOS/index.html).

Data at the NSA OBS site were measured from a 30-m tall tower located in the black spruce forest of about 100 year old (LAI ≈ 4). The tower extends above the canopy height. Flux measurements of CO_2 were collected continuously using the eddy-correlation method. Data collection and processing details are described in detail by (Goulden et al., 1996). A comprehensive set of parameters was observed at this site (e.g. Photosynthetically Active Radiation (PAR), air temperature (T_a) and soil temperature (T_s)).

The measurement tower at Zotino is located in the pine forest with tree age in the range of 50 to 200 years. Measurements started in 1998. They are collected during the warm seasons only using eddy-correlation technique up to a height of 25 m, which is approximately 5 meters above the canopy top.

Nine years of observed data from the NSA OBS site (1995-2003) and three years of observations from Zotino (1999-2001) were used to develop the regression model, which relates Net Ecosystem Exchange (NEE) with meteorological and ecosystem parameters. Data from the NSA OBS site were used for the cold season, since no observations are available for Zotino during this season. The differences between two sites in the combined datasets are characterized by leaf area index and soil properties.

The linear regression models for monthly averaged NEE have been developed in the form

$$y_k = \sum_n b_{k,n} x_{k-\Delta k,n} , \qquad (1)$$

where k is month; Δk=0÷2

$y_k = NEE_k / PAR_k$ for k=4÷10,

$y_k = NEE_k$ otherwise.

Coefficients $b_{k,n}$ are regression parameters. $x_{k,n}$ denote monthly average precipitation (Pr), air temperature (T_a), soil temperature (T_s) and leaf area index (LAI).

2.2.2. Satellite observations as input parameters for regression model

Three of the five parameters (PAR, T_a and LAI) can be potentially estimated from satellite observations with a reasonable accuracy. Two other parameters (Pr and T_s) have to be derived from other sources, synchronous meteorological observations or climate data. Thus, it is possible to apply the regression model (1) for any area that represents boreal

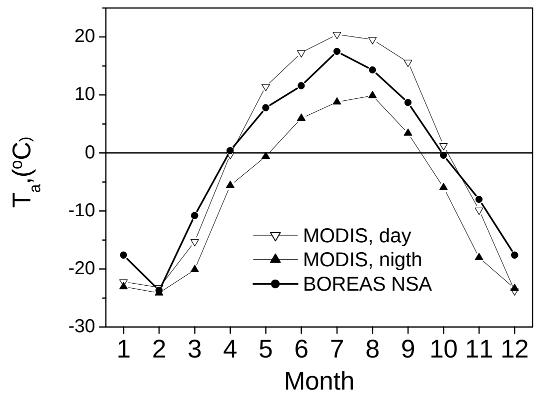

Figure 2. Annual variation of temperatures at the NSA OBS site for 2001.

conifer forest providing that required input data are available or can be estimated from satellite data or other sources.

PAR is one of the major factors influencing plant canopy photosynthesis. This variable can be estimated from satellite observations with a good accuracy. The major factor affecting surface downward PAR flux is a cloudiness. Satellite observing systems provide much information about cloud properties and solar radiation that can be used to estimate PAR. In this work, we used MODIS monthly statistics available from the MOD08_M3 data archive (http://modis-atmos.gsfc.nasa.gov/MOD08_M3/index.html). Two approaches for PAR computation have been developed in this work: 1) A 3D Monte-Carlo Radiative Transfer Model (RTM) with two schemes of broken cloudiness representation (Rublev and Golomolzin, 1992; Rublev et al, 1997; Trembach et al, 2000); 2) A Look-Up Table (LUT) method developed on the basis of stochastic radiative transfer (Titov et al., 1997; Zhuravleva and Firsov, 2004). The comparison between model results and observations revealed a good agreement. Modeled monthly mean fluxes have average bias –3.0 Wm^{-2} relative to observed values with r^2 =0.98 and standard deviation of 5.8 Wm^{-2}.

Various forest parameters (including LAI) can be also determined from satellite data (Cihlar et al., 2003, Trishchenko et al., 2001). Validated LAI data products ove Canada landmass are available from the Canada Centre for Remote Sensing (Fernandes et al., 2003). Global LAI data are also available from MODIS observations (MOD15) (http://modis.gsfc.nasa.gov/data/dataproducts.php?MOD_NUMBER=15#). Combining available validated ground and satellite-based estimates the LAI values of 4 were used for the NSA OBS and 1.5 for Zotino.

The satellite-derived land surface temperature (LST) available from 8-day MODIS composites (MOD11- http://modis.gsfc.nasa.gov/data/dataproducts.php?MOD_NUMBER=11) were utilized as a proxy for air temperature T_a. An example of air temperature and MODIS-derived daytime and nighttime land surface temperatures are presented in Figure 2. To account for the difference between satellite-derived LST and air temperature, we applied a special adjustment procedure. For the warm season (April-October), a nighttime LST increased by 8.5° was employed. For the cold season, a mean daily LST increased by 3.5° was employed.

The total precipitation amount was obtained from the combined precipitation data set available from the Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997). For soil temperature we used average monthly values computed for all observed years.

2.2.3. Simulation of NEE using satellite-derived input

Using the above methodology for determining input parameters we ran our regression model for NEE and compared the results with available observations. The comparison of accumulated monthly mean NEE computed according to model (1) and derived from ground observations is presented in Figure 3 for the NSA OBS site and in Figure 4 for Zotino. Note that, the negative NEE values correspond to a carbon sink in the vegetation.

Typical differences between modeled and observed values are less than 20 gCm^{-2}, which demonstrates a good performance of the developed regression scheme. It should be noted that the range of uncertainty of eddy flux measurements is also quite substantial and can reach ±30 gCm^{-2} per year according to Goulden et al., (1996). The uncertainty of temporal mean values can be as large as -45÷200 gCm^{-2} due to gap filling

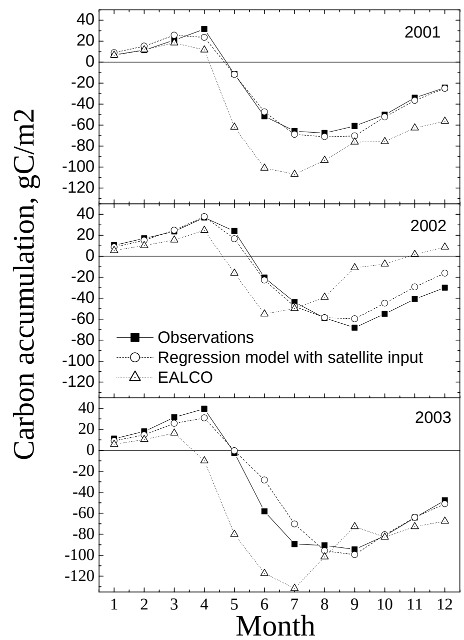

Figure 3. The seasonal dynamics of NEE at NSA OBS.

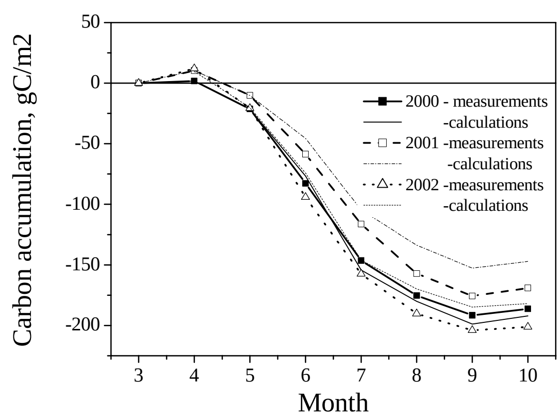

Figure 4. The seasonal dynamics of NEE. Zotino, Russia

techniques (E.Falge et al 2001). Substantial errors can be obtained also due to errors in the specification of T_s, as well as errors in the evaluation of T_a, which cannot be directly observed from satellites and therefore should be either directly measured or estimated from alternative sources

3. ATMOSPHERIC CO_2 FROM SCIAMACHY

The current observing system for carbon dioxide has a significant gap as observations of CO_2 are mostly based on sparsely distributed surface measurements. Although the measurements considered above are rather precise, they are limited to approximately 100 sites around the world and cannot meet the needs for CO_2 global monitoring. The only way to fill this gap and to obtain adequate spatial and temporal global information on CO_2 is to develop the remote sensing techniques capable of retrieving CO_2 column amounts and profiles from satellite-based measurements.

The new instrument SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric Cartography) was launched onboard ENVISAT. One of its goals is a determination of CO_2 abundance in the Earth's atmosphere. A special scheme has been developed by Buchwitz et al. (2004, 2005) for the retrieval of atmospheric constituents including CO_2 from the global nadir measurements of the SCIAMACHY.

Initial CO_2 atmospheric column retrievals obtained from the SCIAMACHY sensor at the Institute of Environmental Physics, University of Bremen indicate that SCIAMACHY is able to detect reduced CO_2 atmospheric column amounts resulting from uptake of CO_2 by the vegetation during growing season (Figure 5). The initial estimates of the regional and latitudinal gradients of CO_2 retrieved from SCIAMACHY are higher than those predicted by chemistry and transport models (Buchwitz et al., 2004). These results are encouraging for the use of SCIAMACHY for studying the carbon cycle. However, the retrieval scheme still requires some improvements, such as more reliable cloud detection and corrections for atmospheric vertical structure and surface albedo variability. An alternative CO_2 retrieval scheme that is based on a fast multi-component regression and an improved treatment of pixel cloud contamination is currently under development.

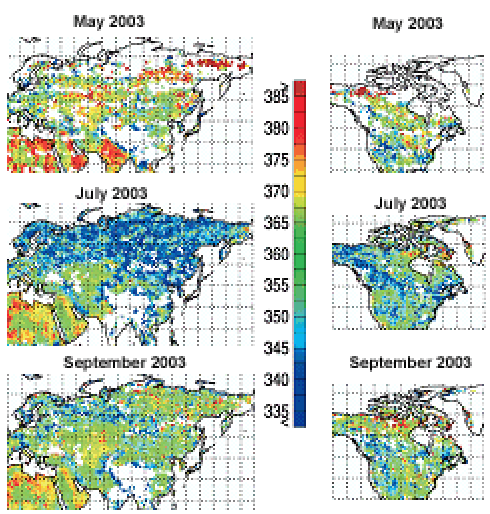

Figure 5. Detecting seasonal variations in the CO_2 column due to vegetation activity. A decreased atmospheric column is observed during the peak of the growing season.

4. TOWARDS RETRIEVAL OF THE ATMOSPHERIC CO_2 CONCENTRATION FROM HIGH RESOLUTION INFRARED SOUNDERS

New capabilities for CO_2 remote sensing are emerging with the development of advanced high-resolution IR sounders like the Atmospheric InfraRed Sounder (AIRS) and the Infrared Atmospheric Sounding Interferometer (IASI). Preliminary feasibility studies have shown promising results for monitoring of carbon trace gases (CH_4, CO) column amounts (Trotsenko et al., 2003), as well as CO_2 column amounts using this type of data (Chédin et al., 2003). The purpose of our present studies is to advance the remote sensing methodology for monitoring CO_2 from advanced IR sounders data through separating effects of cloudiness (Uspensky et al., 2001; Rublev et al., 2004) and temperature/humidity profile variations, and developing CO_2 regression estimation techniques with a careful choice of predictors.

The approach required to solve these problems includes several steps, namely, (a) the updating, adjustment, and validation of existing Forward Radiative Transfer Models (FRTM) for modeling high resolution satellite measurements (AIRS, IASI); (b) the refined analysis of the satellite information content with respect to CO_2 perturbations and the selection of dedicated sensor's channel subset (with minimization of above interfering factor effects); and (c) the development and validation of the regression procedure for CO_2 retrievals.

In order to meet required accuracy levels of CO_2 column retrievals (monthly averaged error ~1 % or better than 4 ppmv) the development of regression techniques must be based on a special choice of predictors (similar to those proposed for retrieval of ozone and water vapor profiles), see (Trotsenko et al., 2003).

5. CONCLUSIONS

The capabilities of satellite observations for the remote sensing of CO_2 surface fluxes and atmospheric concentrations over boreal forests have been analyzed. A novel regression model suitable for calculating various components of CO_2 fluxes at the surface level and employing satellite data as input has been developed. Techniques for estimating input parameters (PAR, air temperature, etc.) from satellite data are proposed. The results are validated against observations and compared to the results produced by the European LPJ dynamic global vegetation model and the Canadian ecosystem model EALCO developed at the Canada Centre for Remote Sensing. The comparison conducted for two boreal sites located in Canada (Manitoba) and Russia (Zotino) shows encouraging agreement. Typical differences between modeled and observed values of annually accumulated NEE are less than 20 gCm^{-2}, which demonstrates a good performance of developed regression scheme.

Initial CO_2 atmospheric column retrievals from SCIAMACHY onboard ENVISAT indicate that it is possible to detect the reduced CO_2 atmospheric column amounts resulting from uptake of CO_2 during the growing season. The initial estimates of the regional and latitudinal gradients of CO_2 retrieved from SCIAMACHY are higher than those predicted by chemistry and transport models, which are crucial for developing reliable “inverse modeling methods”. The potential of combined solar and thermal satellite observations and upcoming IASI/METOP for CO_2 monitoring is briefly discussed and some recommendations have been proposed.

6. ACKNOWLEDGEMENTS

Authors are grateful to Dr. Stephen Sitch for the consultations regarding the use of LPJ-model, and to Dr. Yuri Knyazikhin for some useful suggestions.

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